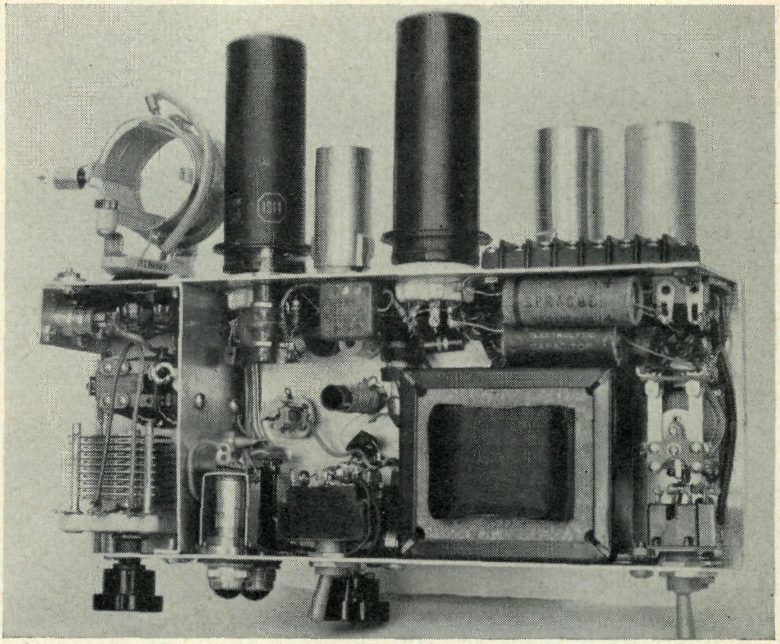
Mobile Reference-Shift Modulator



The author's reference-shift-modulated mobile rig. The modulator (right to left) uses a 12AX7, 12AU7, and 1614 (or 6L6) with modulation choke mounted inside the chassis. Input to final is 35 watts.

Dale L. Hileman, K6DDV
Ramo-Wooldridge Corp.
Inglewood, Calif.

In the design of both mobile and fixed-station rigs, the modulation transformer is an eternal headache. Unless you pay extra for a multimatch transformer, you're limited to only one final-amplifier load impedance. This is especially notable in the case of the mobile rig which will seldom load according to your expectations.

To avoid the transformer problem you can use screen modulation (frequently used in mobile rigs), but this method provides a carrier efficiency of only about 30 per cent. No ordinary efficiency-modulation system can offer the psychological boost to be obtained from a plate-modulation carrier efficiency of 60—80 per cent.

One solution is Heising, or choke-coupled, plate modulation. With Heising plate modulation the final operates at the usual 60—80 per cent class-C efficiency. In this system an ordinary filter choke replaces the modulation transformer. A choke is a common junk-box item; or, if you don't have a choke with suitable characteristics, you can buy one at half the cost of a comparable modulation transformer.

However, the class-A_1 amplifier used in a conventional Heising modulator has two serious shortcomings: First, since the maximum modulator plate dissipation occurs with no audio input the permissible modulator plate-power input is therefore limited to the rated plate dissipation of the tube even though the actual plate dissipation drops below this value with audio input. In other words, you can't take full advantage of the tube's capabilities. Suppose, for example, you use a 6L6 in a conventional class-A_1 modulator. The rated plate dissipation of this tube is about 20 watts; therefore you're limited to 20 watts input to the modulator. But with maximum audio input,

A transformerless plate modulator for a 35-watt mobile rig

the actual plate dissipation drops to 13 watts or less. This leaves 7 watts or more of potential plate dissipation that goes unused.

Second, the maximum plate-current swing is severely limited; hence, maximum modulator plate efficiency is usually only about 30 per cent.

Both of these objections can be overcome by a circuit in which modulator plate current is reduced in the absence of audio input. By this means, the full plate-dissipation capability of the tube can be utilized and the power input thereby increased. Also, the greater plate-current swing increases efficiency. In fact, if linearity can be maintained, the theoretical maximum efficiency of 50 per cent can be obtained.

Two systems which fulfill these requirements have recently appeared in *CQ:* The first, and by far the oldest, is bias-shift modulation, rejuvenated in 1950 by M. H. Kronenberg[1] and modernized in 1954 by Bill Orr[2]. In this system, the modulator tube is operated class-A_1 and control-grid bias is varied according to the audio level. An increasing audio level decreases the bias and consequently increases modulator plate current.

The other variable-plate-current Heising system is called "class-K" modulation and was developed by the author[3],[4] in 1953. In the class-K system, the modulator (*not* the r-f final) is fitted with an audio-controlled clamp tube. An increasing audio level increases the audio-clamp-tube bias and thereby increases the modulator screen voltage. The modulator is operated at zero bias so that a high plate-current swing can be obtained within a reasonable screen-voltage excursion.

Both systems provide a high modulation level, good efficiency, and excellent linearity. However, each has its drawbacks. The bias-shift system requires the use of a fixed-bias supply and one or two bias-control tubes, which contribute to physical size, complexity, and cost. These factors are particularly important in the design of a mobile modulator.

The class-K system, while requiring no fixed-bias supply, does use a power-consuming audio clamp tube. And because this modulator is operated at zero bias, it requires considerable driving power, which means that the driver consumes appreciable d-c input power. Power-supply drain is of course another important consideration in the mobile modulator.

Reference-shift plate modulation combines the better features of the bias-shift and class-K systems and avoids the disadvantages of both. No fixed-bias supply is needed, no unwieldy clamp tube is used, and the driver requires very little input power. This modulation system is therefore particularly well suited to the mobile rig.

Reference-Shift Modulation

Reference-shift plate modulation is basically bias-shift modulation with positive bias. Don't be alarmed: Positive bias has no ill effect since the modulator tube is operated as a zero-bias triode.

The unique cathode-follower driver circuit which makes a practical reference-shift modulator possible was suggested to me by Henry S. Keen, W2CTK. Mr. Keen had devised a controlled-carrier screen-modulation system in which the d-c output level of the modulator is a function of the audio input voltage[5]. Mr. Keen suggested that his modulator might be an excellent *driver* for a variable-plate-current Heising plate modulator. He was quite right.

Detailed operation of the reference-shift plate modulator is described in the April issue of Radio & Television News[6]. However, here is a brief circuit analysis:

The basic reference-shift circuit is shown in *Fig. 1.* The output of cathode-follower driver *V1* is an audio voltage impressed on a positive d-c voltage equal to the peak audio voltage. The average plate current of modulator *V2* is therefore proportional to the audio input voltage.

Voltage divider *R3* and *R4* applies a fraction of the cathode voltage to the anode of rectifier *CR1*. Output from *CR1* is filtered by *C2* and applied as a positive d-c reference level to the grid through grid-return resistor *R1*.

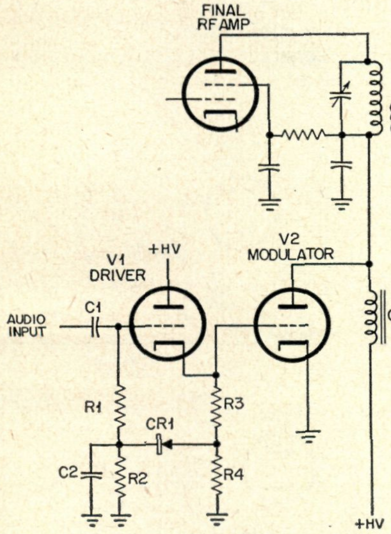


Fig. 1. Basic reference-shift modulator. Choice of values is discussed in the text.

1. M. H. Kronenberg, "Low Cost Modulator for the KW Final," *CQ*, Oct., 1950, p. 34.
2. Orr, "The Bias-Shift Modulator," *CQ*, April, 1954, p. 33.
3. Hileman, "Class K Modulator," *CQ*, Oct., 1953, p. 37.
4. Hileman, "Class K Mobile Modulator," *CQ*, Sept., 1954, p. 16.
5. A similar system is described in *CQ:* Thomas E. Beling, "The Midget Budget Modulator," *CQ*, September, 1955, p. 45.
6. Hileman, "A Reference-Shift Modulator," Radio & Television News, April, 1955, p. 46.

Resistor *R2* permits *C2* to discharge at a syllabic rate but not an audio rate. The reference voltage is therefore a function of the average audio level.

With no audio input, *V1* is biased by the voltage developed across *R3*. This voltage is high enough that the plate current of *V1*, and therefore the cathode voltage, is relatively low. But audio voltage applied to the grid through *C1* causes an audio voltage to be added to the already-existing d-c voltage at the junction of *R3* and *R4*. The resulting increase in reference voltage increases the average cathode current, which in turn increases the d-c cathode level. The d-c output level of *V1* thus increases as its audio output level increases.

Modulator *V2* is a zero-bias triode operated with positive bias; this bias is the d-c output level of *V1*. Since the d-c output level of *V1* is a function of the audio level, the average plate current of *V2* is also a function of the audio level.

With no audio input, therefore, the plate current of *V2* is at its minimum value. With maximum audio input, the plate current is at its maximum average value, swinging between cutoff and saturation. This plate-current swing provides a plate efficiency of 50 per cent or more.

Compared with the characteristics of a conventional class-A_1 modulator, the increased efficiency of a reference-shift plate modulator and the increase in permissible power input *almost triple the obtainable power output*. Thus where a 6L6 normally provides a power output of 7 watts, in a reference-shift circuit it delivers an output of almost 21 watts.

The 6L6 is of course not a zero-bias triode; it is a tetrode. However, any tetrode can be made to operate as a zero-bias triode, as explained later.

Choice of Values

Driver *V1* should have a relatively low plate resistance so that a low source impedance is presented to the grid of *V2*. And the maximum rated cathode-to-heater voltage of *V1* must be high enough to permit a relatively high peak-positive output voltage. Among the tubes that fulfill these requirements for low- or medium-power applications are the 6BF5 (triode connected), 6C4, 6S4, 12AU7, and 12BH7.

Resistors *R3* and *R4* should be equal in value. The mathematical proof of this statement is somewhat involved; however, experimental evidence bears it out.

These resistors are simply a voltage divider, loaded by a relatively high impedance, and should not present an appreciable load to *V1* compared to the grid-to-cathode resistance of *V2*. The total resistance of *R3* and *R4* should be 5 to 10 times the load presented by the grid of *V2*.

Rectifier *CR1* must have a maximum rated back voltage equal to or higher than the maximum reference voltage. A 1N38 will tolerate a back voltage of about 100 volts; for a higher voltage, a thermionic rectifier (such as the 6AL5) is most practical. Crystal diodes in series are not recommended; two cost more than one 6AL5 and cannot be depended on to have equal back resistances.

The time constant of components in the cathode circuit of *CR1* is not at all critical but

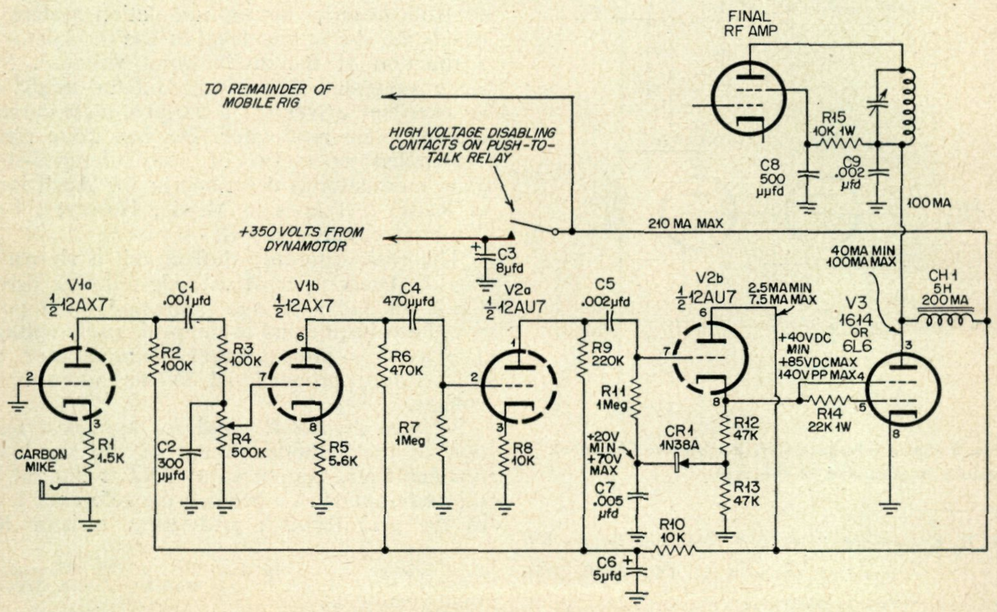


Fig. 2. Complete schematic diagram for the mobile reference-shift modulator.

Parts List

C1—0.001 μfd., 500 v.
C2—330 μμfd., 500 v.
C3—8 μfd., 450 v. electrolytic
C4—470 μμfd., 500 v.
C5—0.002 μfd., 500 v.
C6—5 μfd., 450 v. electrolytic
C7—0.005 μfd., 500 v.
C8—500 μμfd., 1000 v. (see text)
C9—0.002 μfd., 1000 v. (see text)
CH1—5 henries, 200 ma
CR1—1N38A diode
J1—microphone jack, as required
R1—1500 ohms, ½ w.
R2, R3—100,000 ohms, ½ w.
R4—500,000-ohm potentiometer
R5—5600 ohms, ½ w.
R6—470,000 ohms, ½ w.
R7, R11—1 meg., ½ w.
R8, R10—10,000 ohms, ½ w.
R9—220,000 ohms, ½ w.
R12, R13—47,000 ohms, ½ w. (5%)
R14—22,000 ohms, 1 w.
R15—10,000 ohms, 1 w. (see text)
V1—12AX7 tube
V2—12AU7 tube (do not
V2—12AU7 tube (do *not* use 12AX7 for *V2*)
V3—1614 or 6L6 tube (1614 preferred)

should be as small as will permit full reference voltage for the lowest audio frequencies involved. Experimental data indicate that a time constant of 0.005 to 0.05 sec is satisfactory.

The reactance of *C2* at audio frequencies should be 2 to 5 times the resistance of *R3* or *R4* so that it charges quickly as the audio level increases. With a given value for *C2*, therefore, the time constant is determined primarily by the resistance across *C2*. So if *CR1* is a thermionic rectifier having an almost infinite back resistance, the time constant is determined by the value of *R2*. But if *CR1* is a crystal rectifier, then its back resistance may determine the time constant, making *R2* unnecessary.

The resistance of *R1* is the normal grid-return value for *V1*. Coupling capacitor *C1*, however, should be as small as practicable to that it has negligible effect on the time constant.

I have referred to modulator *V2* as a zero-bias triode; actually a triode has probably never been used as a reference-shift modulator. Instead, tetrodes have been used. Modulator input voltage is applied directly to the screen grid and to the control grid through a current-limiting resistor, a method commonly used in class-B zero-bias modulators using tetrodes.

Experiments with several tetrodes indicate that a tetrode reference-shift modulator requires a maximum d-c screen-voltage input level equal to one-third the value necessary for class-C operation.

The reactance of modulation choke *CH1* (at about 200 cps) should be equal to or higher than the power-amplifier plate impedance. Its current capacity should be about equal to the sum of the modulator and final plate currents. The lower its d-c resistance, the better.

For a high modulation level, the modulator must deliver an output power equal to half the input power to the final r-f amplifier. The maximum plate efficiency of a reference-shift moduator is 50 per cent; therefore, maximum modulator power input is equal to final r-f amplifier power input. For the same reasons, the modulator should have a rated plate dissipation equal to at least half the final power input.

In a conventional class-A_1 Heising plate modulator, a d-c voltage-dropping network is required between the modulator plate and the final to produce 100 per cent modulation. However, in a reference-shift circuit, the modulator plate-current swing is great enough that a voltage-dropping network is unnecessary. This system provides a modulation level which for all practical purposes is equivalent to that of a conventional class-B modulator.

A Mobile Modulator

A schematic of the mobile reference-shift modulator is shown in *Fig. 2*. The speech amplifier uses three triode sections; *V1a*, *V1b*, and *V2a*. Section *V2b* is a cathode-follower driver for modulator *V2*.

Input amplifier *V1a* is a grounded-grid stage, eliminating the need for an expensive and bulky microphone transformer; sections *V1b* and *V2a* are conventional cascaded triodes. These three stages provide enough gain to make cathode-bypass capacitors unnecessary.

Frequency response of the modulator is determined by circuit constants in the speech amplifier. Low-frequency response is limited by the low values of coupling capacitors *C1* and *C4;* high-frequency response is limited by *R3* and *C2* in the grid circuit of *V1b*. Values for these components are so chosen that response is 1 db down at 500 cps and 2500 cps, limits customarily recommended for amateur modulators. However, many operators prefer more high-frequency response in a mobile rig. Therefore, to boost high frequencies, simply exclude *R3* and *C2*.

Reserve gain is sacrificed to eliminate cathode-bypass capacitors. However, any of the speech-amplifier cathode resistors may be bypassed if more gain is needed.

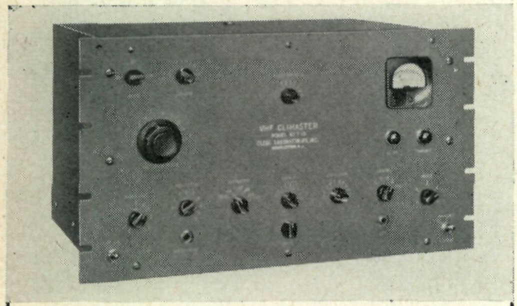
Capacitors *C3* and *C6* and resistor *R10* are a dynamotor hash filter. They are not necessary if the mobile-power-supply output is well filtered.

Values in the driver circuit were chosen in accordance with the principles described under "Design Considerations." Rectifier *CR1* is a 1N38A; any diode having a rated back voltage of 100 volts or more and a nominal back resistance greater than 0.5 meg. is satisfactory. However, if you use a thermonic rectifier or a diode having a back resistance exceeding 3 meg., connect a 1.5-meg. resistor across *C7*.

A 6L6 operates satisfactorily for modulator *V2*. A 1614, however, is a better choice since it offers a higher plate-dissipation rating at no increase in physical size.

Choke *CH1* should have an inductance of

[*continued on page 100*]



MOBILE REFERENCE-SHIFT MODULATOR

[*from page 39*]

at least 5 h. and a current-carrying capacity of approximately 200 ma.

Important voltages and currents are shown on the schematic, *Fig. 2*. Total current drain is 210 ma. max.; 100 ma. for the final, 100 ma. max. for the modulator, and 10 ma. max. for the driver and speech amplifier. Optimum plate voltage is 350—375 v.

Values for *C8*, *C9*, and *R15* in the final plate and screen circuits depend on the tube used. Values shown are typical for a *1614* or 6L6. The voltage rating of both *C8* and *C9* should be at least twice the plate voltage.

Audio quality is good; the modulation level is equivalent to or higher than that of any conventional modulator running the same maximum input power.

I have not included a description of the r-f section of the rig since your judgment in this matter is probably as good as or better than mine. However, my rig uses a 6AH6 series-tuned Clapp vfo (screen resistor 220,000 ohms and grid resistor 22,000 ohms) doubling in the plate circuit from 160M to 75M. The final is a 1614 operating straight through on 75M.

Construction

Placement of components is not critical; a reference-shift modulator should be laid out according to the same principles that apply to any ordinary modulator.

The reference-shift-modulated rig shown in the photograph was built on an LMB 144 box chassis. This chassis consists of two members which form a rectangular box. The member not shown is mounted under the dash with two bolts. When the rig is in place, tubes face the firewall and controls face the front seat. The rig occupies a space under the dash only 2-½ in. high and 10 in. long.

Components are admittedly crowded. I do not recommend you attempt such compact construction unless you are outstandingly patient.

However, if you do use an LMB 144 box chassis, replace the screws that hold the chassis together. The two 6-32 machine screws supplied are not adequate. Replace them with two no. 8 x ¼-in. sheet-metal screws.

Conclusion

The reference-shift circuit provides a simple and inexpensive means for obtaining high-level plate modulation without transformers and is particularly well adapted for use with low-power rigs. I hope that other experimenters will investigate the possibilities of this circuit; and I enthusiastically welcome correspondence on the subject of variable-plate-current Heising modulation systems. ■